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TAPCO GROUP

Thompson Ramo Wooldridge Inc.

May 28, 1963

SUBJECT: Erratum on Quarterly Reports. No. 2 and 3
Contract No. N600 (19) 58831
Fracture Characteristics of Structural Metals.

Gentlemen:

Due to an error in the temperature measuring device used in the low temperature tests in the subject contract, the actual test temperatures were -45 and +40°F instead of -100 and 0°F as reported. The corrected data and additional data for -100°F will be reported in the final report, which will be available in July, 1963.

Very truly yours,

THOMPSON RAMO WOOLDRIDGE INC.

G L Hanna

G. L. Hanna
Materials Research and Development

GLH:wl

63-3-1

TM 3642-67

THIRD QUARTERLY PROGRESS REPORT
TO
BUREAU OF NAVAL WEAPONS RRMA-223
NAVY DEPARTMENT

FRACTURE CHARACTERISTICS OF STRUCTURAL METALS

CONTRACT No. N 600 (19) 58831

31 MARCH 1963

$4.60

MATERIALS DEVELOPMENT DEPARTMENT
TAPCO
A DIVISION OF
Thompson Ramo Wooldridge Inc.
CLEVELAND 17, OHIO

TAPCO a division of Thompson Ramo Wooldridge Inc.

FRACTURE CHARACTERISTICS OF STRUCTURAL METALS

Quarterly Report No. 3
Covering Period
1 January 1963 to 31 March 1963

TM 3642-67

Prepared Under Department of the Navy
Bureau of Weapons

Contract No. N600 (19) 58831

Submitted By

G. L. Hanna
E. A. Steigerwald

31 March 1963

Materials Research and Development Department
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ABSTRACT

During this reporting period, the plane strain fracture toughness (K_{IC}) was determined for three heats of 4340 steel tempered to produce tensile strengths of 200,000 and 280,000 psi, and three heats of beta titanium aged 72 hours at 900°F. Tests were conducted on both bar and sheet material over a test temperature range of -100 to 300°F.

The results indicated that the K_{IC} values determined from heats obtained as bar stock and tested with circumferentially - precracked specimens were always significantly larger than those obtained from precracked sheet specimens. Considering only the test results obtained at room temperature, the 4340 sheet materials, at a 280,000 psi tensile strength level, showed an average plane strain fracture toughness value of 40,000 psi$\sqrt{in}$; the 4340 at a 200,000 psi tensile strength level had a K_{IC} value of 66,600 psi$\sqrt{in}$; while the beta titanium had a K_{IC} value of 30,000 psi$\sqrt{in}$.

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I INTRODUCTION

Although many of the conventional ultra high-strength steels are capable of attaining yield strengths as high as 250,000 psi, in actual practice their useful strength level is limited by severe notch embrittlement. This type of embrittlement can be realistically described as a decrease in material reliability since it results in a relatively high probability for component failure at stresses below the design level.

A problem exists in selecting a parameter which will provide the designer with an indication of the reliability of a material in a particular application. Although several methods for evaluating the notch properties of materials are currently being considered (1,2,3)*, the use of the fracture mechanics parameter, plane strain fracture toughness (K_{IC}), has stimulated the largest degree of interest and has attained some acceptance (1). The purpose of this program is to evaluate the possibility of employing plane strain fracture toughness (K_{IC}) as a handbook value to rate the fracture characteristics of high-strength metals. This parameter is particularly attractive since it not only represents a material constant which can provide for meaningful qualitative comparisons between materials, but it also has the possible advantage of allowing quantitative predictions to be made of the load-carrying capacity of a component.

Progress Report No. 1 (4) presented a literature survey which indicated that the existing data on plane strain fracture toughness (K_{IC}), was insufficient to allow it to be critically evaluated as a possible handbook parameter. As a result an experimental program was initiated to determine K_{IC} for beta titanium, 4340, H-11, and the maraging steels. The test program, the test methods and the mechanical properties of three heats of the maraging steels, in sheet form were reviewed in Progress Report No. 2. This Third Quarterly Progress Report presents the complete test results obtained on beta titanium and 4340 steel.

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* Numbers in parentheses pertain to references in the Bibliography.

II MATERIALS

The following four materials were selected for the test program:

1. 4340 steel
2. H-11 die steel
3. 18% nickel maraging steel
4. Beta titanium

A summary of the material variables included in the program is presented in Table I. Both 4340 and H-11 were chosen as materials presently included in MIL Handbook 5, while the beta titanium and maraging steels represent high-strength materials which will possibly be included in future handbook sections.

The pertinent data on the test materials are summarized in Table II. All the heats of the 4340 and H-11 steels conformed to their respective AMS specificationswhile the beta titanium and the maraging steels were within accepted compositional limits.

Representative microstructures of the beta titanium and the 4340 steels, which were tested during this reporting period, are presented in Figures 1 through 3. The austenitizing treatments on the 4340 steel were performed in neutral salt baths and tempering was done in air furnaces. Approximately 0.005" was ground from each face of the steel sheet specimens after heat treatment to eliminate any surface effects. The round specimens were finished machined and precracked after heat treatment.

The beta titanium was received from the mill in the solution treated condition and heat treatment was performed by aging for 72 hours at 900°F in vacuum. All the sheet titanium specimens were pickled after aging in an aqueous solution of 30% HNO_3 and 3% HF.

TABLE I

Summary of Material Variables to be Tested

Material	Heat No.	Form	Direction	Heat Treatment
4340 Steel	124515	Bar	L	1700°F Normalize (20 min. in salt)
	768236	Sheet	L and T*	1550°F Austenitize (20 min. in salt)
	768657	Sheet	L and T	(a) 400°F temper (1 hr + 1 hr) (b) 750°F temper (1 hr + 1 hr)
H-11 Steel	06826	Bar	L	1850°F Austenitize (20 min. in salt)
	05716	Sheet	L and T	(a) 1000°F temper (2 hrs + 2 hrs) (b) 1050°F temper (2 hrs + 2 hrs) (c) 1100°F temper (2 hrs + 2 hrs) (d) 1150°F temper (2 hrs + 2 hrs)
18 Ni-9Co-5Mo	06498	Sheet	L and T	1500°F Anneal (1 hr)
Maraging Steel	W-24178	Sheet	L and T	900°F Aged (3 hrs)
18 Ni-7Co-5Mo	06759	Bar	L	1500°F Anneal (1 hr)
Maraging Steel	24285	Sheet	L and T	900°F Aged (3 hrs)
Beta Titanium	F6997	Bar	L	
(B120 VCA)	F7769	Sheet	L and T	900°F Age (72 hrs)
	F7798	Sheet	L and T	

* Tests in the transverse direction are in all cases to be made at room temperature only. Longitudinal tests will be made over a range of temperatures between -100 and 300°F.

TABLE II

Materials

Material	Thickness	Vendor	Heat No.	C	Si	Mn	Cr	V	Mo	Co	Ni	S	P	Others
4340 Low Alloy Martensitic Steel														
Bar	1" Dia.	Crucible	124515	0.40	0.23	0.77	0.86	-	0.26	-	1.72	0.019	0.018	.10Cu, .01 Sn
Sheet	0.063"	Acme	7C8236	0.41	0.27	0.67	0.80	-	0.21	-	1.82	0.016	0.008	
Sheet	0.063"	Ziegler	7C8657	0.41	0.31	0.74	0.81	-	0.24	-	1.78	0.019	0.008	
H-11 Hot-work Die Steel														
Bar	1" Dia.	Vanadium Alloys	06826	0.41	0.82	0.22	5.15	0.52	1.22	-	-	0.005	0.010	
Sheet	0.080"	Vanadium Alloys	05716	0.43	0.96	0.25	5.12	0.54	1.33	-	-	0.007	0.010	
18% Nickel Maraging Steel														
Bar (250)*	1" Dia.	Vanadium Alloys	06759	0.02	0.10	0.08	0.04	-	4.78	7.22	18.20	0.010	0.004	0.50 Ti, 0.10 Al, 0.06 Cu, 0.005 B, 0.020 Zr, 0.05 Ca
Sheet (250)	0.070"	Allegheny Ludlum	24285	0.007	0.01	0.03	-	-	4.82	7.45	18.32	0.006	0.001	0.10 Al, 0.39 Ti, 0.005 Ca, 0.005 Zr, 0.002 B
Sheet (300)	0.063"	Vanadium Alloys	06498	0.02	0.04	0.07	-	-	4.93	9.10	18.36	0.008	0.007	0.10 Al, 0.60 Ti, 0.05 Ca, 0.02 Zr, 0.0026 B
Sheet (300)	0.070"	Allegheny-Ludlum	W-24178	0.012	0.01	0.01	-	-	4.92	8.90	18.69	0.005	0.003	0.029 Al, 0.62 Ti 0.006 Ca, 0.003 Zr, 0.002 B

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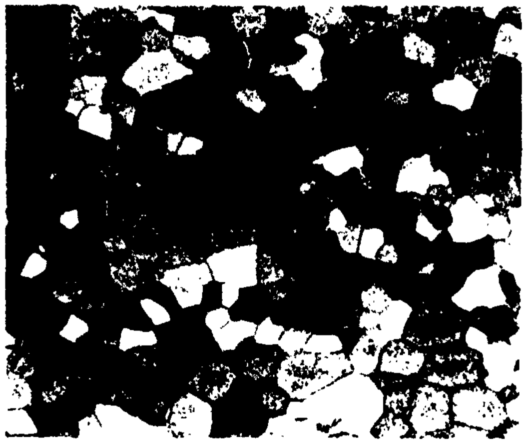
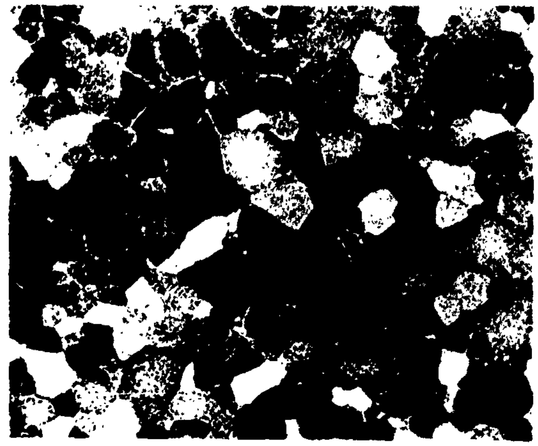
TABLE II
(Continued)

Material	Thickness	Vendor	Heat No.	C	Al	V	Cr	H_2	O_2	N_2	Fe
Beta Titanium (B120 VCA)											
Bar	1" Dia.	Crucible	F6997	0.04	3.2	13.25	10.9	0.0154	0.18	0.02	0.26
Sheet	0.040"	Crucible	F7769	0.02	3.0	13.7	11.2	0.0180	.0.10	0.02	0.23
Sheet	0.040"	Crucible	F7798	0.02	3.1	13.8	10.8	0.0124	0 10	0.02	0.23

* Denotes Strength level attainable in 1000 psi.



6146 HEAT F7798



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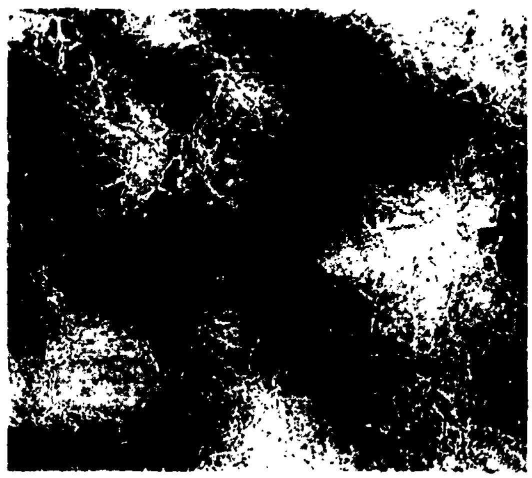
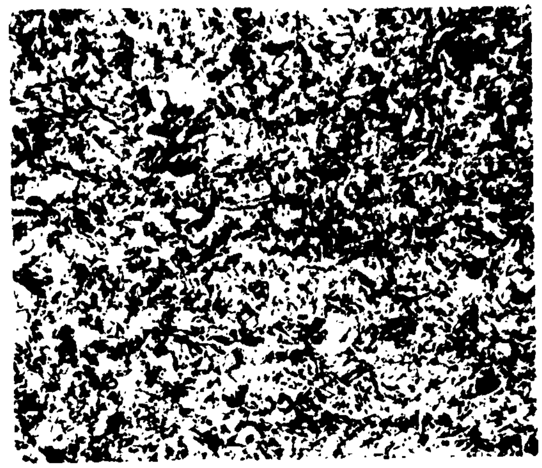


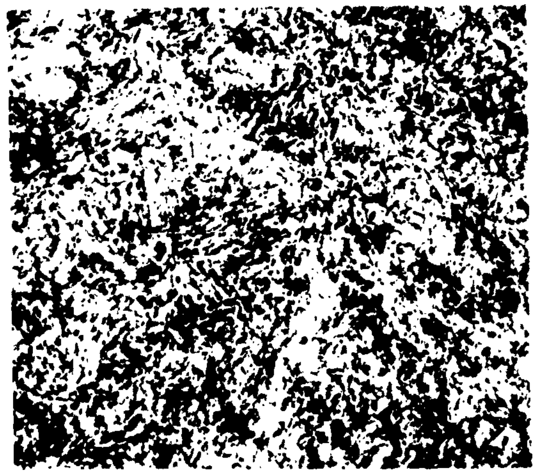
6803 HEAT F6947

FIG. 1: MICROSTRUCTURE OF B120VCA TITANIUM, AGED 72 HOURS AT 900°F IN VACUUM: ETCHANT: $\frac{1}{2}$% HF IN WATER. 100 X

6812 HEAT 7C-8236

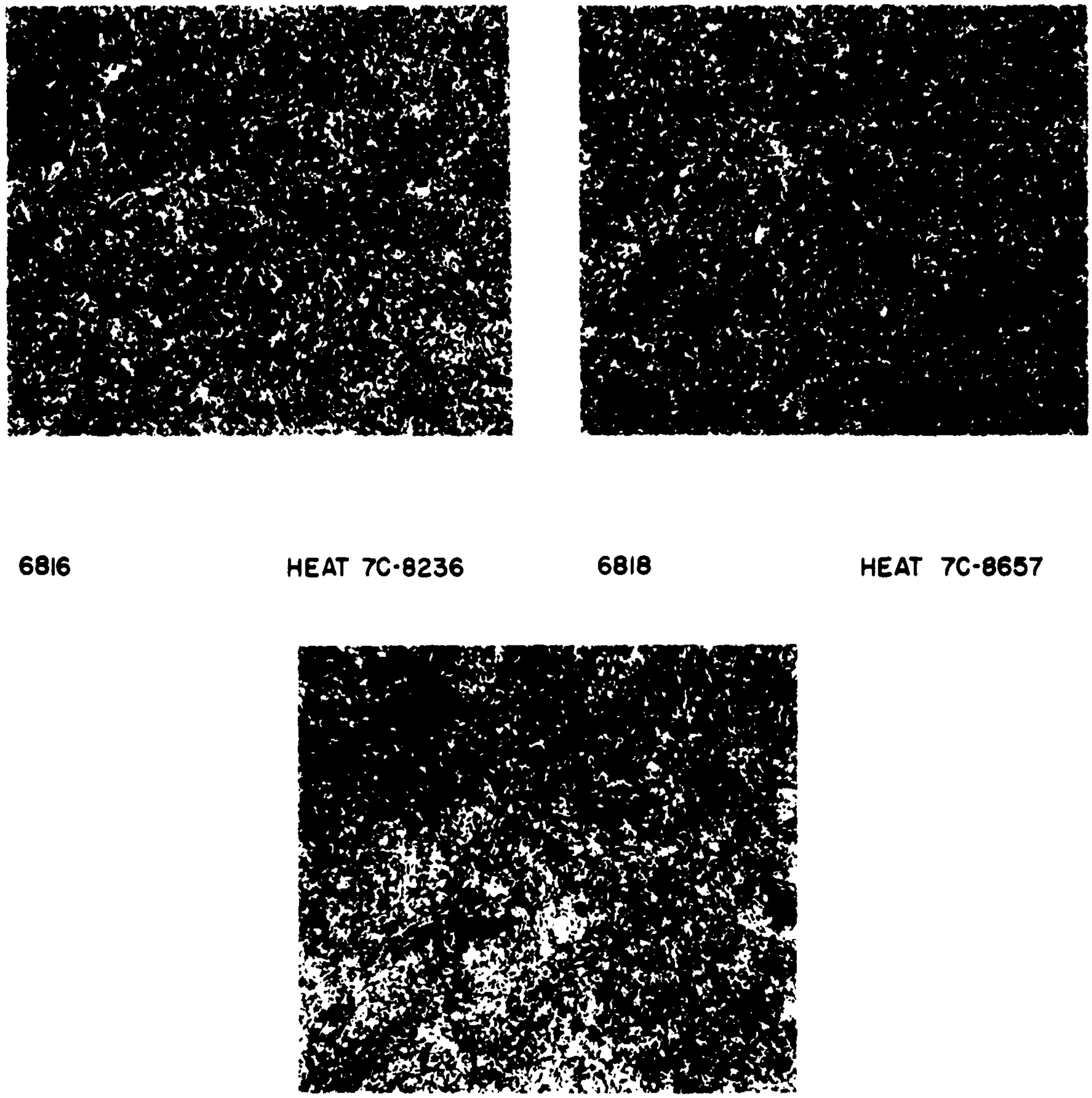


6810 HEAT 7C-8657



6808 HEAT 124515

FIG. 2: MICROSTRUCTURE OF 4340 STEEL, AUSTENITIZED AT 1550° F, OIL QUENCHED, TEMPERED AT 400° F; ETCHANT: 2% NITAL. 500 X



6816 HEAT 7C-8236

6818 HEAT 7C-8657

6814 HEAT 124515

FIG. 3: MICROSTRUCTURES OF 4340 STEEL, AUSTENITIZED AT 1550°F, OIL QUENCHED, TEMPERED AT 750°F; ETCHANT 2% NITAL. 500 X

III TEST METHODS

The test methods which have been previously described (4), involve the determination of plane strain fracture toughness (K_{IC}) with both center-notched, precracked sheet specimens and circumferentially-precracked round specimens. The geometries of the test specimens are presented in Figures 4, 5, and 6. All specimens were precracked after heat treatment. The crack was generated in the sheet specimens by tension-tension fatigue and in the bar specimens by rotating the sample under a fixed bending moment. The circumferentially-notched specimens were all tested in a concentric loading apparatus to insure an eccentricity less than 0.001".

Tests were conducted at temperatures of -100, 0, 75, 200, and 300°F. A loading rate of approximately 500 psi/min. was employed for the notch specimens and a 0.010"/min. strain rate was used on the smooth specimens. The low-temperature tests were performed in a special apparatus, described in the Quarterly Progress Report No. 2, which employed liquid nitrogen vapor. The tests above room temperature were conducted in conventional resistance-heated furnaces.

In sheet specimens the plane strain fracture toughness was calculated from an experimental determination of the load at which slow crack growth was initiated. Resistance measurements were used to measure the point of slow crack initiation (5) and the K_{IC} parameter was calculated by using the modified Irwin tangent formula (1). In the tests on circumferentially-notched bars the plane strain fracture toughness was obtained directly from the net notch tensile strength. A discussion of the specific methods employed for calculating K_{IC} is given in Appendix I.

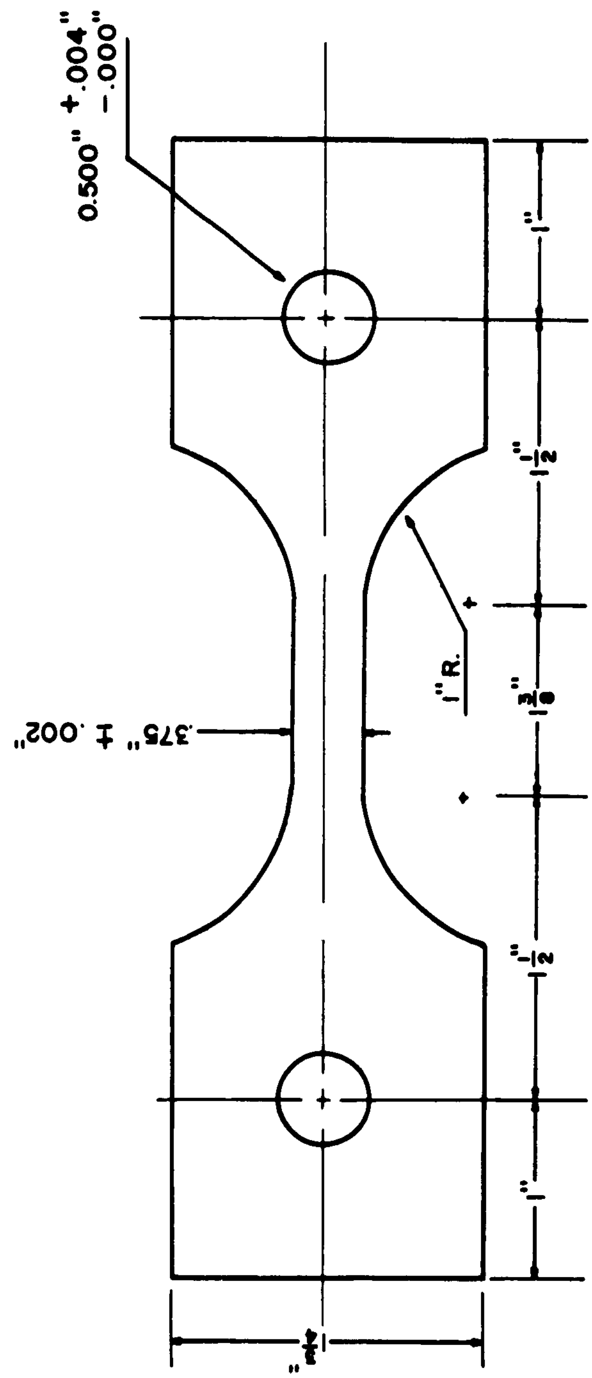


FIG. 4: SMOOTH SHEET TENSILE SPECIMEN GEOMETRY.

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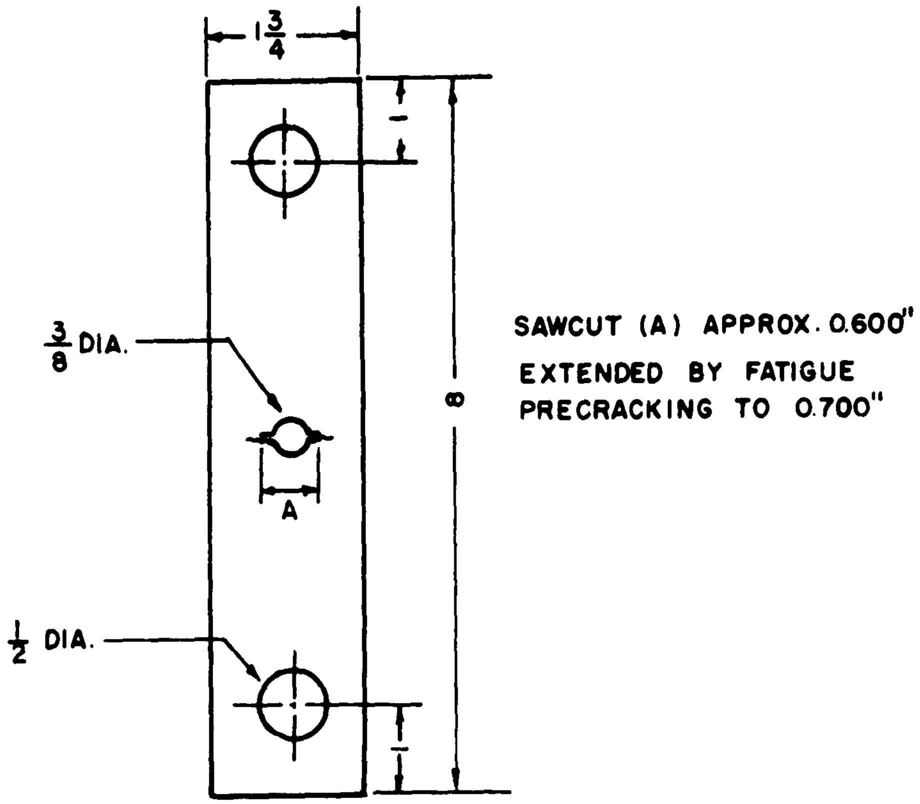

FIG. 5: CENTER PRECRACKED NOTCH TENSILE SPECIMEN

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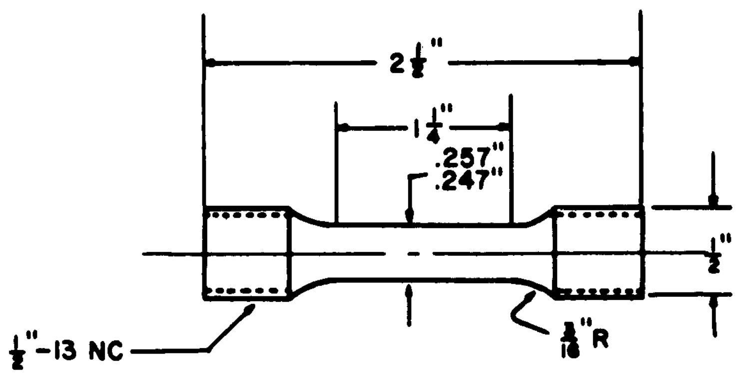
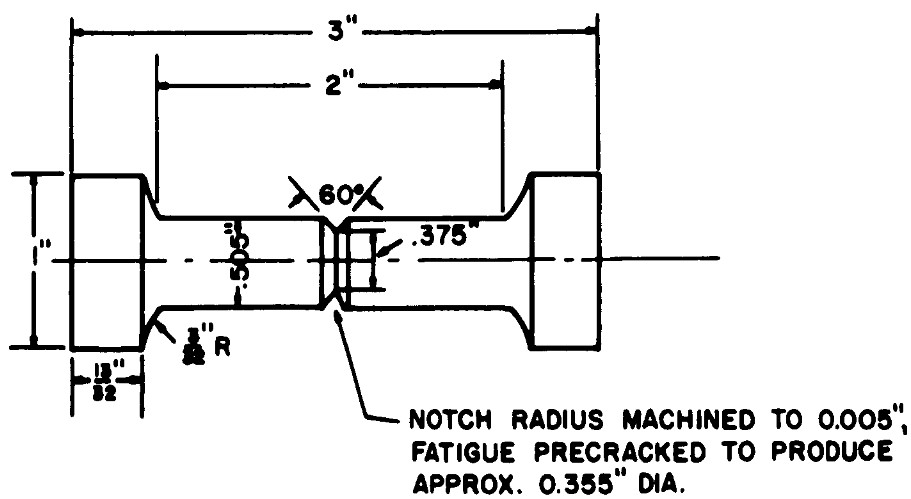


SMOOTH TENSILE SPECIMEN



NOTCH TENSILE SPECIMEN

FIG. 6: GEOMETRY OF TEST SPECIMENS FOR BAR STOCK.

IV RESULTS AND DISCUSSION

1. Beta Titanium

The smooth strength properties of three heats of beta titanium aged 72 hours at 900°F are presented in Figure 7*. The results indicate that a rather wide variation in strength properties occurred between heat F7798 (sheet) and heats F7769 (sheet) and F6997 (bar). The smooth strength decreased rather consistently as a function of increasing test temperature and this strength decrease was attended by a slight increase in tensile ductility.

The notch tensile properties of the beta titanium are shown in Figure 8. A transition in fracture appearance occurred in the sheet material at approximately 200°F. The notch tensile strength, defined as the load at fracture divided by the cross-sectional area in the plane of the notch, steadily increased with increasing test temperatures. Due to the increased constraint involved in circumferentially-notched specimens the notch strength was considerably higher than that obtained with sheet samples. The plane strain fracture toughness for the beta titanium is presented in Figure 9 as a function of test temperature. At temperatures below approximately 100°F both heats of sheet material had comparable plane strain fracture toughnesses, however at higher temperatures the lower strength heat had slightly greater K_{IC} values. A comparison between the two heats with comparable yield strengths (heat 7769 sheet and heat 6977 bar) indicated that at all test temperatures the bar stock had K_{IC} values which were approximately 5000 psi$\sqrt{in}$ greater than those obtained with sheet specimens from heat 7769. There is still some question as to whether this degree of difference is due to real variations in material or simply to inaccuracies in the formulas used to calculate K_{IC}. Previous work with aluminum from a single heat has indicated that K_{IC} values determined from round specimens are slightly higher than those obtained from tests with sheet specimens (6).

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* Smooth tensile, notch tensile, and plane strain fracture toughness data for all the materials covered in this report are presented in Tables III through XI.

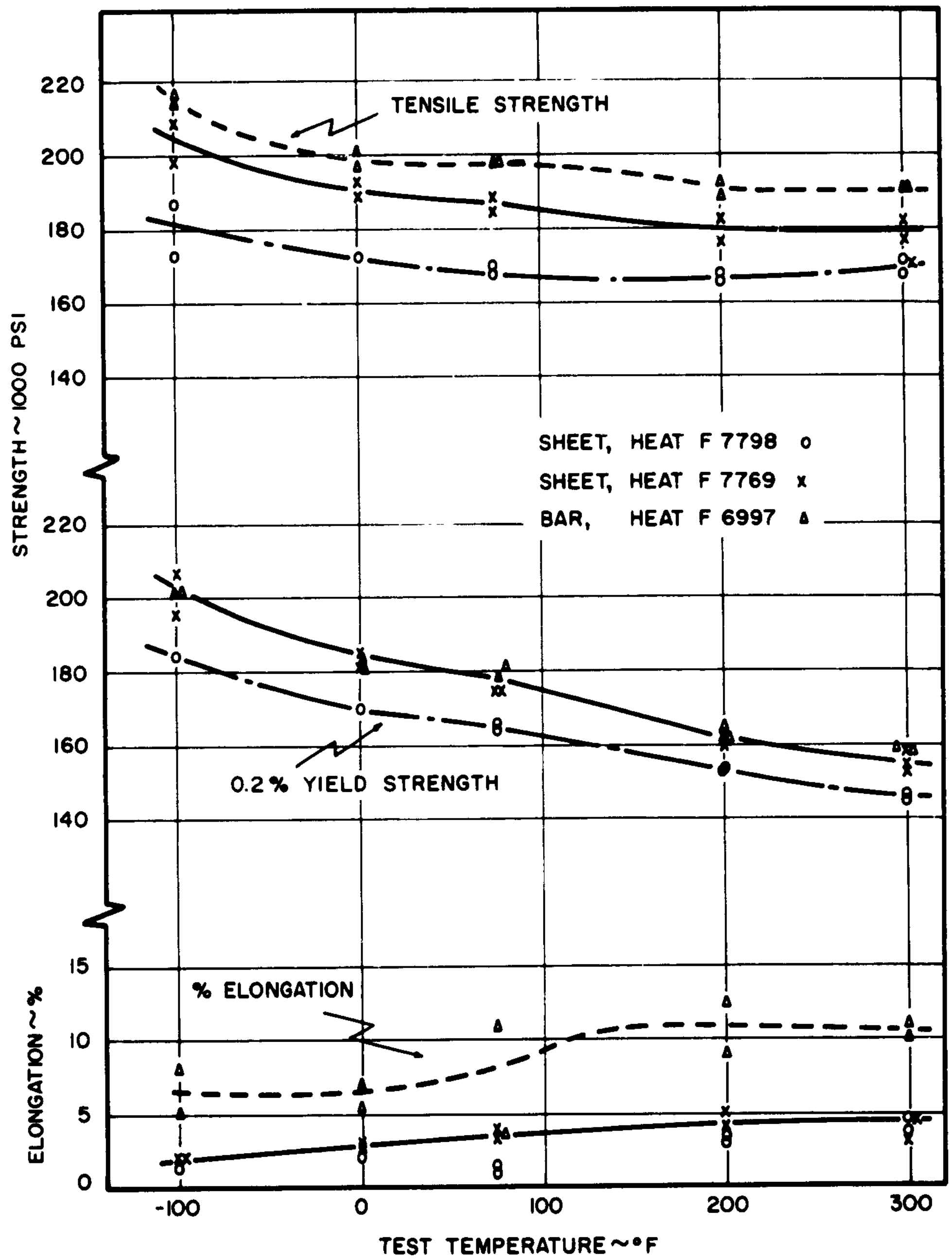

FIG. 7: SMOOTH TENSILE PROPERTIES OF THREE HEATS OF B 120 VCA TITANIUM, AGED AT 900° F FOR 72 HOURS IN VACUUM, LONGITUDINAL DIRECTION.

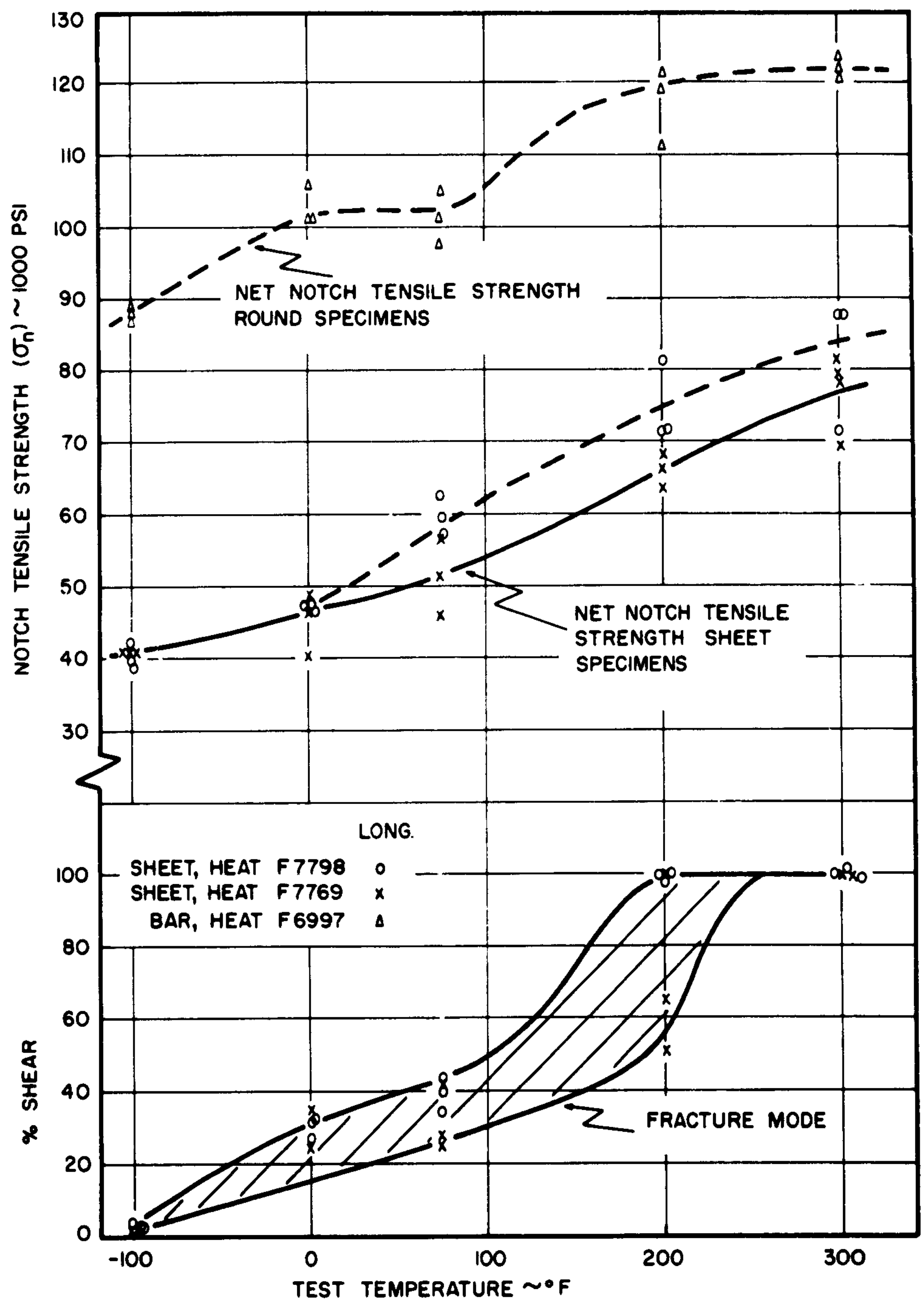

FIG. 8: NOTCH PROPERTIES OF THREE HEATS OF B120 VCA TITANIUM, LONGITUDINAL DIRECTION.

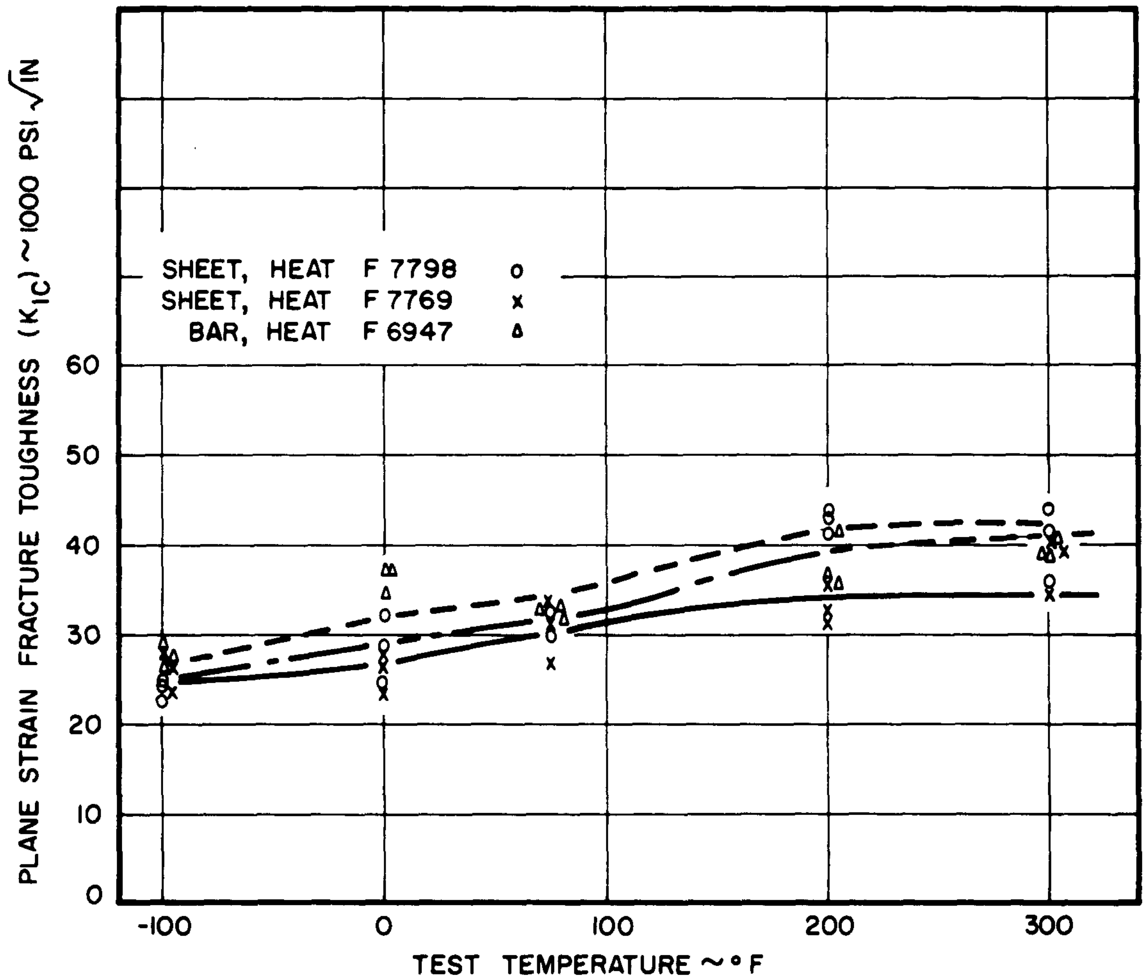

FIG. 9: PLANE STRAIN FRACTURE TOUGHNESS OF THREE HEATS OF B 120 VCA TITANIUM, AGED AT 900° F FOR 72 HOURS IN VACUUM, LONGITUDINAL DIRECTION.

2. <u>4340 Steel, Tempered at 400°F</u>.

The smooth tensile properties of three heats of 4340 steel, tempered at 400°F are presented in Figure 10. The reproducibility between heats was excellent and the properties conformed to previously published data (7).

The notch tensile strengths of the 4340 steels are shown in Figure 11 as a function of test temperature. A comparison between the sheet materials (heat 7C-8236 and 7C-8657) indicates that significant differences occurred in notch properties. The notch tensile strength did not continually rise with increasing test temperature but reached a maximum at approximately 100°F. This decrease in notch properties at higher test temperatures has been previously studied and is caused by a strain aging effect which occurs in this type of high-strength steel (8). These results also indicate that K_{IC} at the higher temperatures would be strain rate dependent.

The plane strain fracture toughness K_{IC} for the 4340 steels (see Figure 12) indicates an overall trend comparable to that exhibited by the notch tensile strength. In the sheet material heat 7C-8236 had K_{IC} values which were slightly higher than heat 7C-8657. As in the case with beta titanium the K_{IC} values obtained from round specimens of 4340 were somewhat greater over the entire test temperature range than those obtained from either heat of sheet material.

3. <u>4340 Steel, Tempered at 750°F</u>.

The reproducibility between smooth tensile properties of the three heats of 4340 tempered at 750°F is illustrated in Figure 13 which shows the strength as a function of test temperature. The tensile strength was relatively insensitive to temperature while the yield strength progressively decreased from 205,000 psi at -100°F to 178,000 psi at 300°F. The notch properties shown in Figure 14 were insensitive to temperature in the -100°F to 100°F temperature range. At higher temperatures however a decrease in notch properties took place presumably due to the strain aging embrittlement which is directly comparable to blue brittleness in mild steels. All the fractures modes in the -100°F to 300°F range were full shear.

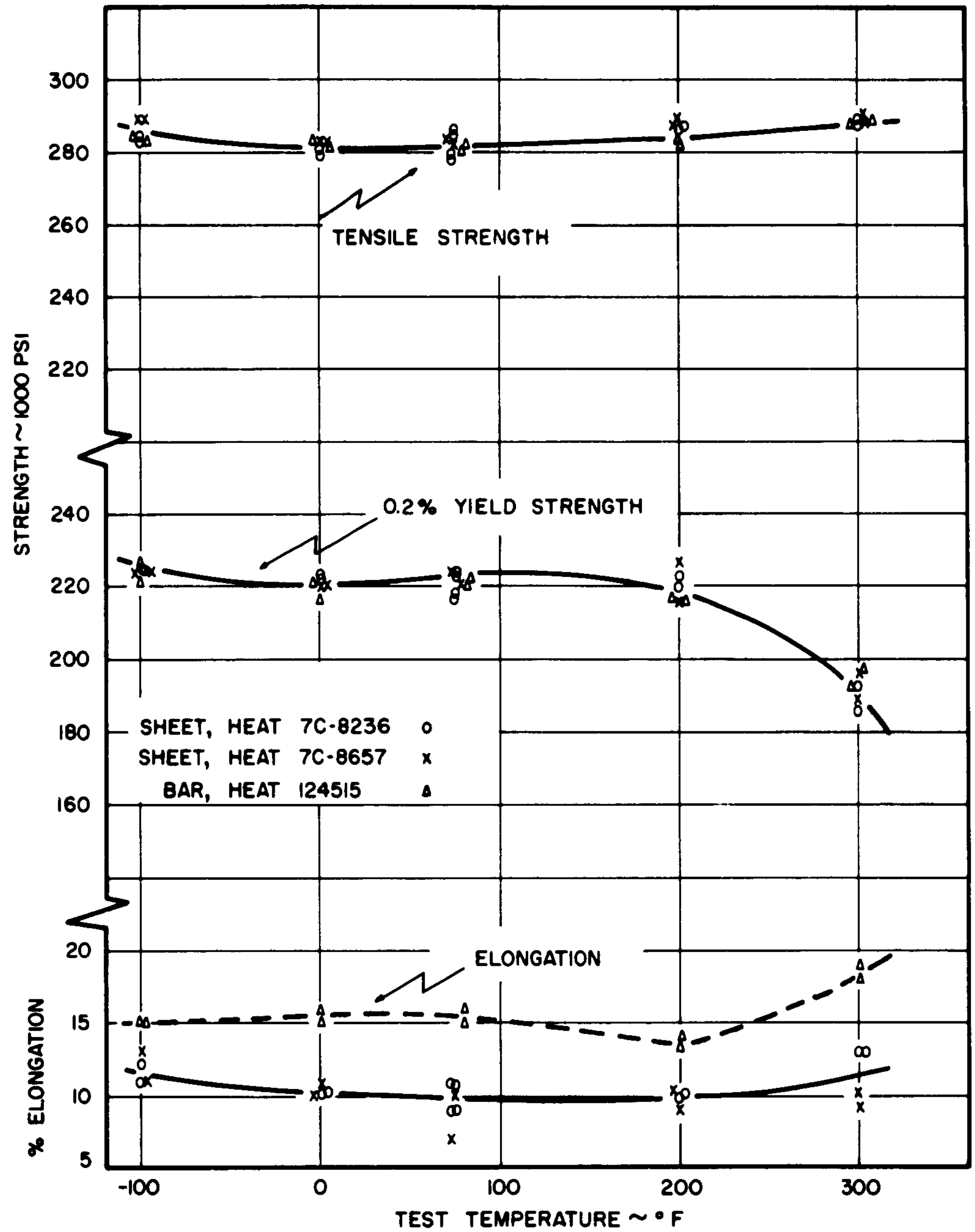

FIG. 10: SMOOTH TENSILE PROPERTIES OF THREE HEATS OF 4340 STEEL, AUSTENITIZED AT 1550° F, OIL QUENCHED, TEMPERED AT 400° F, LONGITUDINAL DIRECTION.

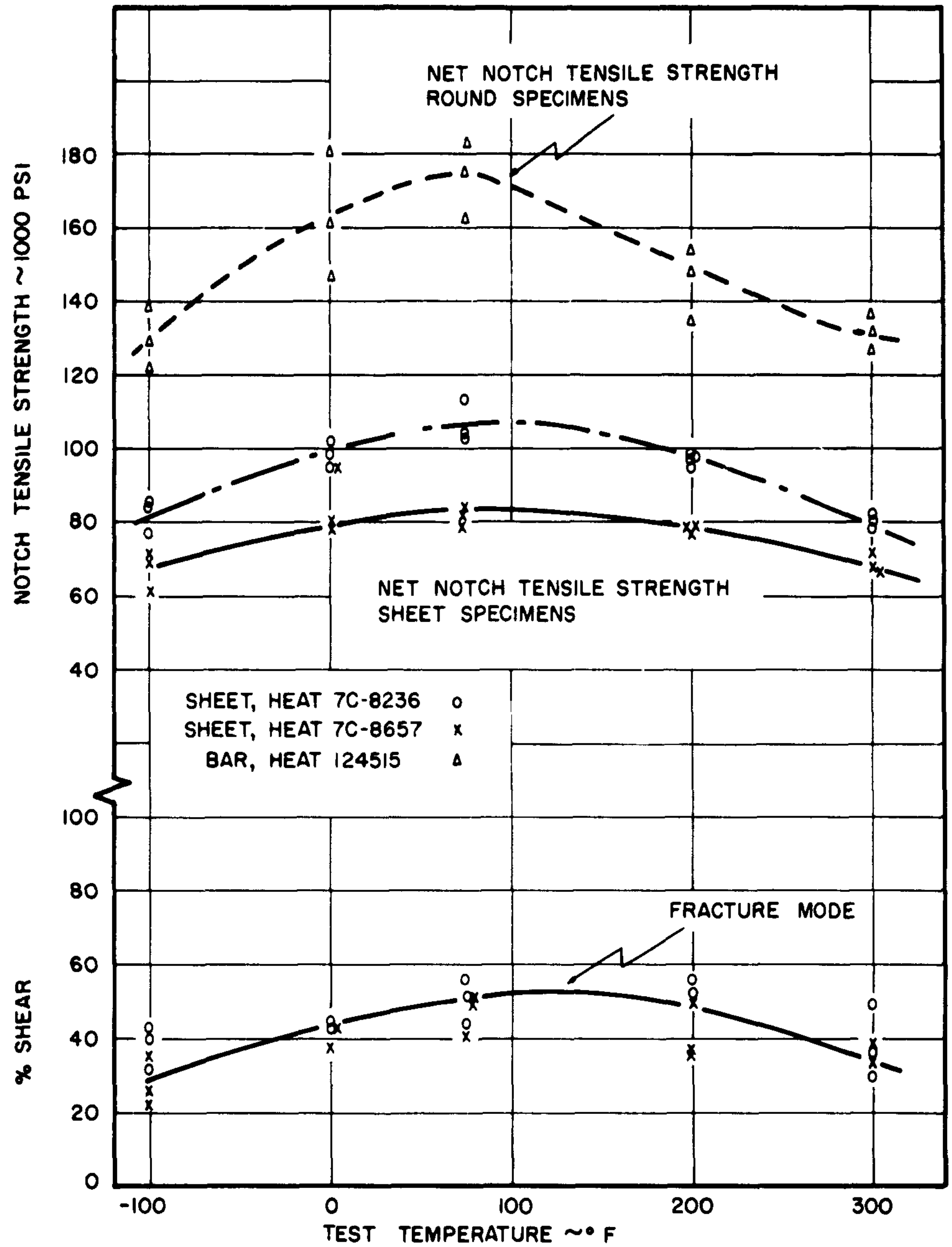

FIG. 11: NOTCH TENSILE PROPERTIES OF THREE HEATS OF 4340 STEEL, AUSTENITIZED AT 1550°F, OIL QUENCHED, TEMPERED AT 400°F, LONGITUDINAL DIRECTION.

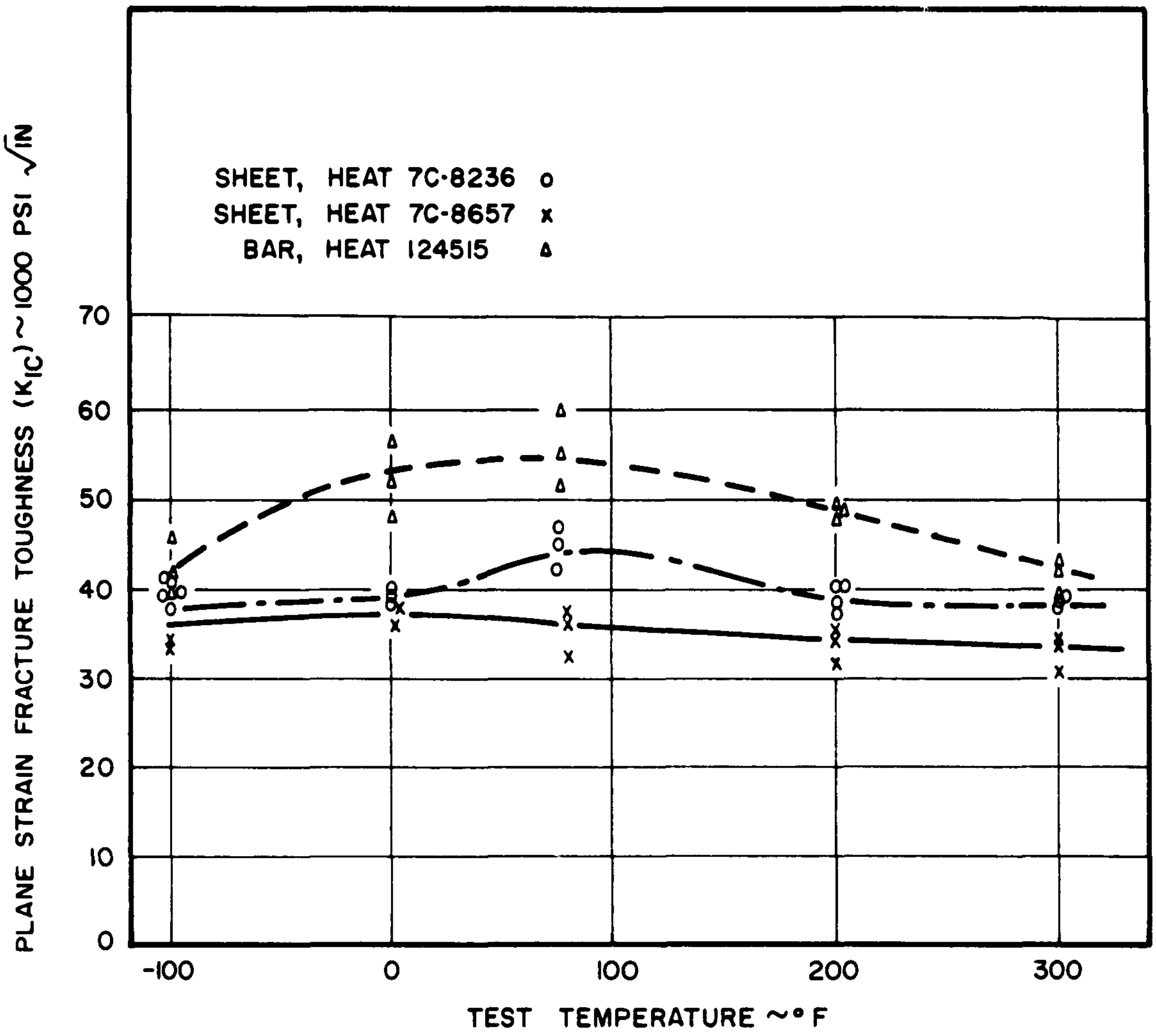

FIG.12: PLANE STRAIN FRACTURE TOUGHNESS OF THREE HEATS OF 4340 STEEL, AUSTENITIZED AT 1550°F, OIL QUENCHED, TEMPERED AT 400°F, LONGITUDINAL DIRECTION.

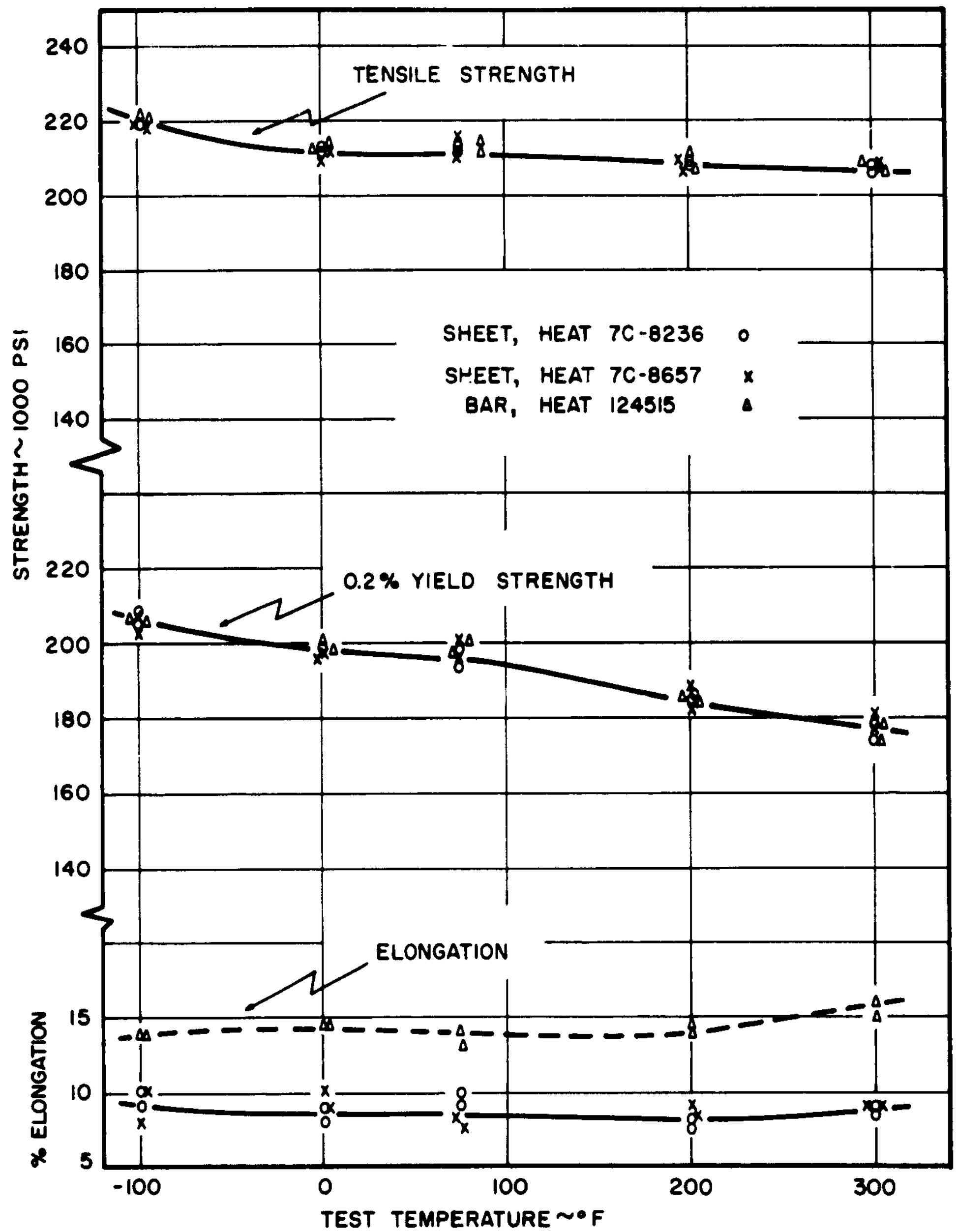

FIG.13 : SMOOTH TENSILE PROPERTIES OF THREE HEATS OF 4340 STEEL, AUSTENITIZED AT 1550° F, OIL QUENCHED, TEMPERED AT 750° F, LONGITUDINAL DIRECTION.

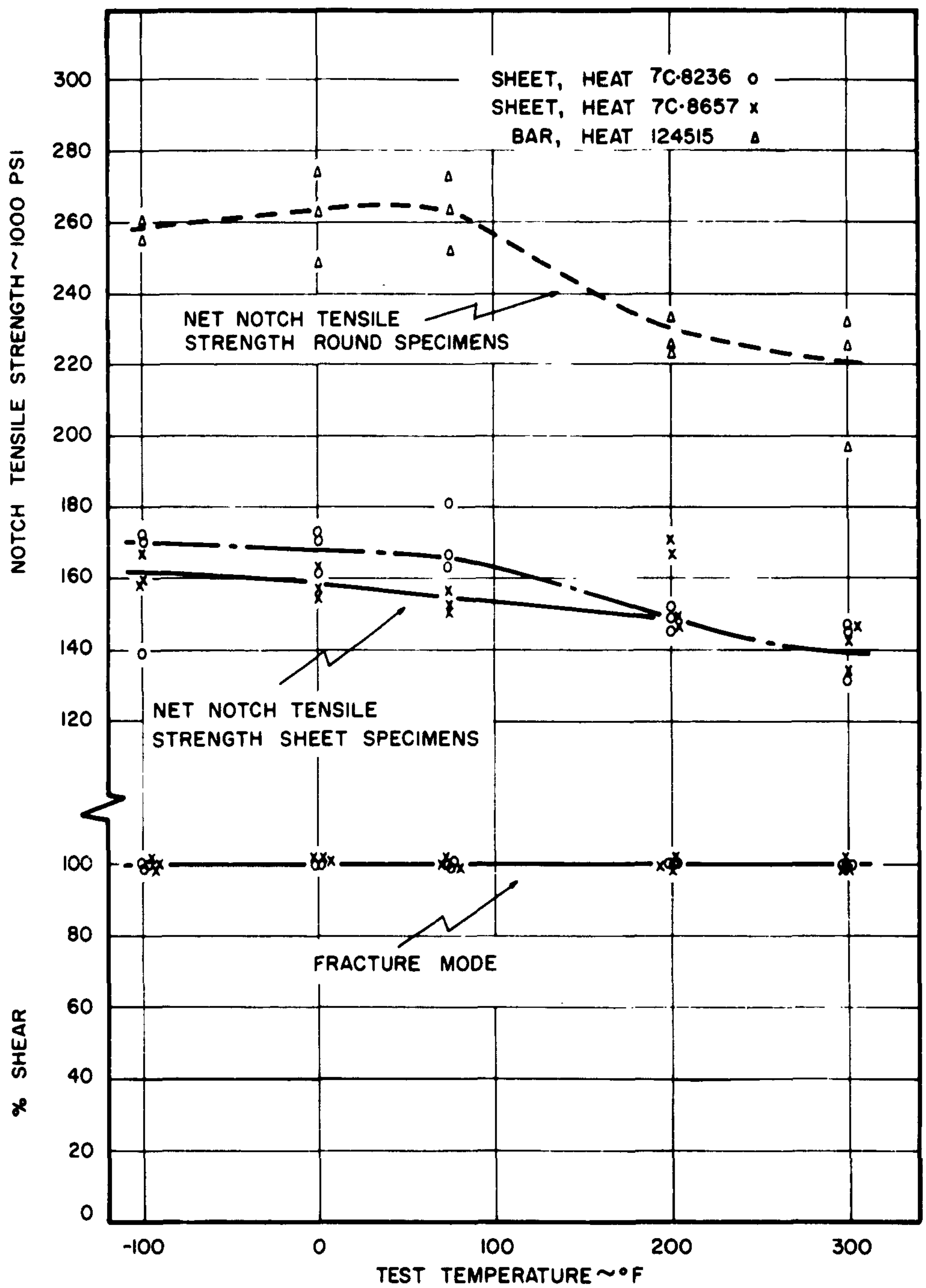

FIG.14: NOTCH TENSILE PROPERTIES OF THREE HEATS OF 4340 STEEL, AUSTENITIZED AT 1550° F, OIL QUENCHED, TEMPERED AT 750° F, LONGITUDINAL DIRECTION.

The plane strain fracture toughness of the 4340 steel, illustrated in Figure 15, was found to be dependent on the particular heat. In agreement with the results obtained on 4340 tempered at 400°F (see Figure 12), heat 7C-8236 had a plane strain fracture toughness which was superior to heat 7C-8657. The K_{IC} values obtained from circumferentially-notched bar specimens of heat 124515 were consistently higher than those calculated from data derived from the sheet specimens. In addition, the K_{IC} values determined from the round samples were obtained under conditions where yielding occurred ($\sigma_N/\sigma_y > 1$), at the cross-section of the notch. Under these conditions in precracked specimens the measured K_{IC} may be lower than the K_{IC} value obtained with larger specimens (6).

4. K_{IC} as a Handbook Parameter

Although the results of the test program are not completed, sufficient data exist to allow a brief discussion on the feasibility of employing K_{IC} as a handbook parameter to rate the fracture characteristics of materials. The results presented in Figure 16 for the three materials tested in sheet form indicate that K_{IC} provides a sensitive evaluation parameter to rate various materials and heat treatments. By comparison, however, K_{IC} is not very sensitive to variations in test temperature.

Results presented in Quarterly Report No. 2 indicated that a coefficient of variation ($\sigma/\bar{x}$) between 2.71 and 7.14% could be expected in a particular determination of K_{IC} for the maraging steels. On this basis the observed differences in K_{IC} between material type, material heat treatment, and heat of material have a high probability of being significant.

In considering K_{IC} for handbook presentation two problems are immediately apparent:

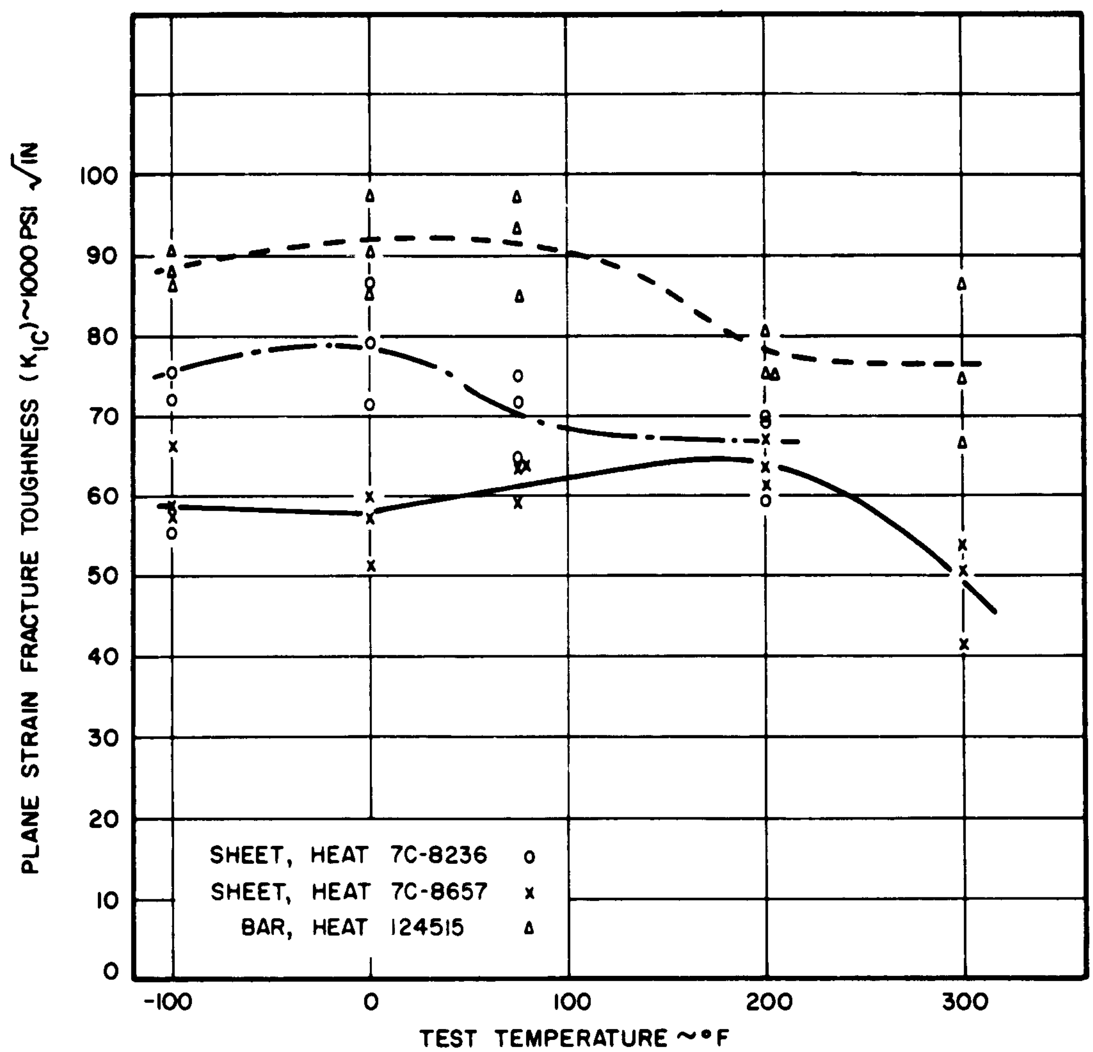

FIG. 15: PLANE STRAIN FRACTURE TOUGHNESS OF THREE HEATS OF 4340 STEEL, AUSTENITIZED AT 1550°F, OIL QUENCHED, TEMPERED AT 750°F, LONGITUDINAL DIRECTION.

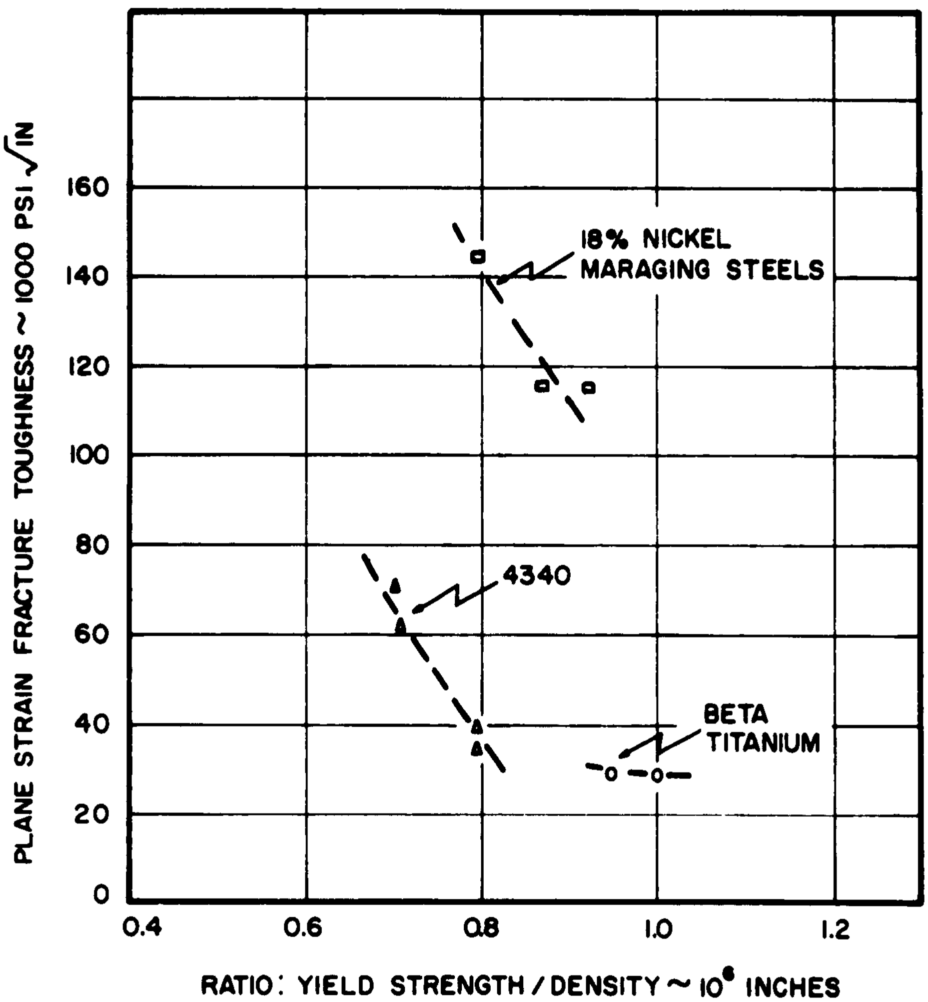

FIG.16: COMPARISON OF PLANE STRAIN FRACTURE TOUGHNESS OF VARIOUS HIGH-STRENGTH MATERIALS AT ROOM TEMPERATURE, SHEET MATERIALS, LONGITUDINAL DIRECTION.

1) Any fracture parameter such as K_{IC} which measures "sharp-notch properties" will show large variations between heats compared to the variations normally experienced in smooth properties. This indicates that at a given smooth strength level a handbook parameter such as K_{IC} would probably be reported as a range or as a typical value since the number of tests required to obtain the A and B statistical parameters would be exceptionally large.

2) The fact that the parameter is independent of specimen dimensions and is a true material constant has been consistently shown in tests which involve only one type of specimen, hence involve only one particular stress analysis to calculate K_{IC}. The current results however indicate that the plane strain fracture toughness values obtained from round specimens are always greater than those obtained from sheet samples. Additional work is needed to determine if this difference is really due to an improved fracture toughness present in the bar stock or if it is merely a result of employing equations to calculate K_{IC} which are not completely satisfactory. Until this difficulty is resolved, K_{IC} data reported in handbook form should be obtained from test methods which produce consistent comparisons between material and which do not interject significant variations due to test method.

V FUTURE WORK

Test will be completed with circumferentially - precracked specimens to determine the K_{IC} values on the maraging steels from heat 06759.

Two heats of the H-11 hot-work die steel will be evaluated to determine plane strain fracture toughness. One heat will be tested in bar form, the other as sheet material.

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VII APPENDIX I

Methods Used to Determine K_{IC}

The methods by which the plane strain fracture toughness can be calculated from sheet specimens was presented in detail in Appendix I of the Second Quarterly Progress Report.

The K_{IC} values can be computed from circumferentially-precracked round specimens by employing the method used by Carman, Armiento, and Markus (9):

$$K_{IC} \left[1 - \frac{p\, K_{IC}^{2}}{2\pi \sigma_y^{2}\, d} \right]^{2} = 0.233\ \sigma_n \sqrt{\pi D} \qquad (1)$$

where:

K_{IC} = plane strain fracture toughness

p = constant $1/\sqrt{2}$

σ_y = 0.2% yield strength

d = specimen diameter at the base of the notch

σ_n = net notch tensile strength

D = major specimen diameter

This equation which applies when the ratio d/D is equal to 0.707 can be rewritten in the form:

$$X \left[1 - 1/2\ X^{2} \right]^{2} = 0.233\ \frac{\sigma_n}{\sigma_y} \qquad (2)$$

where:

$$X = \frac{K_{IC}}{\sigma_y} \frac{1}{\sqrt{\pi D}} \qquad (3)$$

Equation 2 is presented in graphical form in Figure 17. Plane strain fracture toughness can be determined from this figure from a knowledge of the σ_n / σ_y ratio.

In actual experimental practice it is difficult to accurately control the precrack to produce exact d/D values of 0.707. Variations from this ideal d/D ratio were taken into account by applying the corrections factors described by Wundt (10). These corrections factors are plotted as a function of d/D in Figure 18. In practice the K_{IC} values calculated from equation 3 and Figure 17 were multiplied by the appropriate correction factor given in Figure 18 to produce the reported values of plane strain fracture toughness.

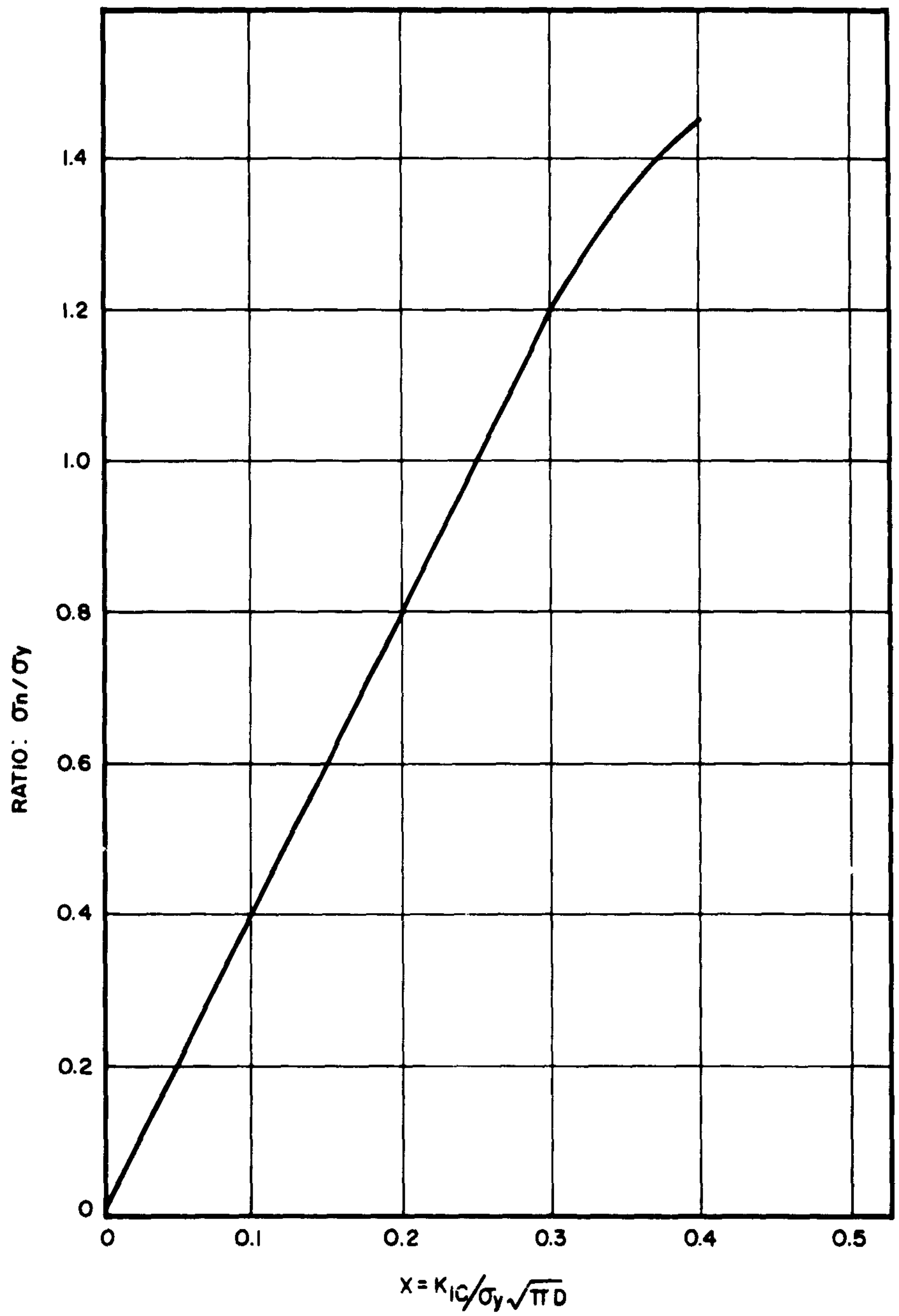

FIG. 17: GRAPHICAL METHOD FOR DETERMINING K_{IC}.

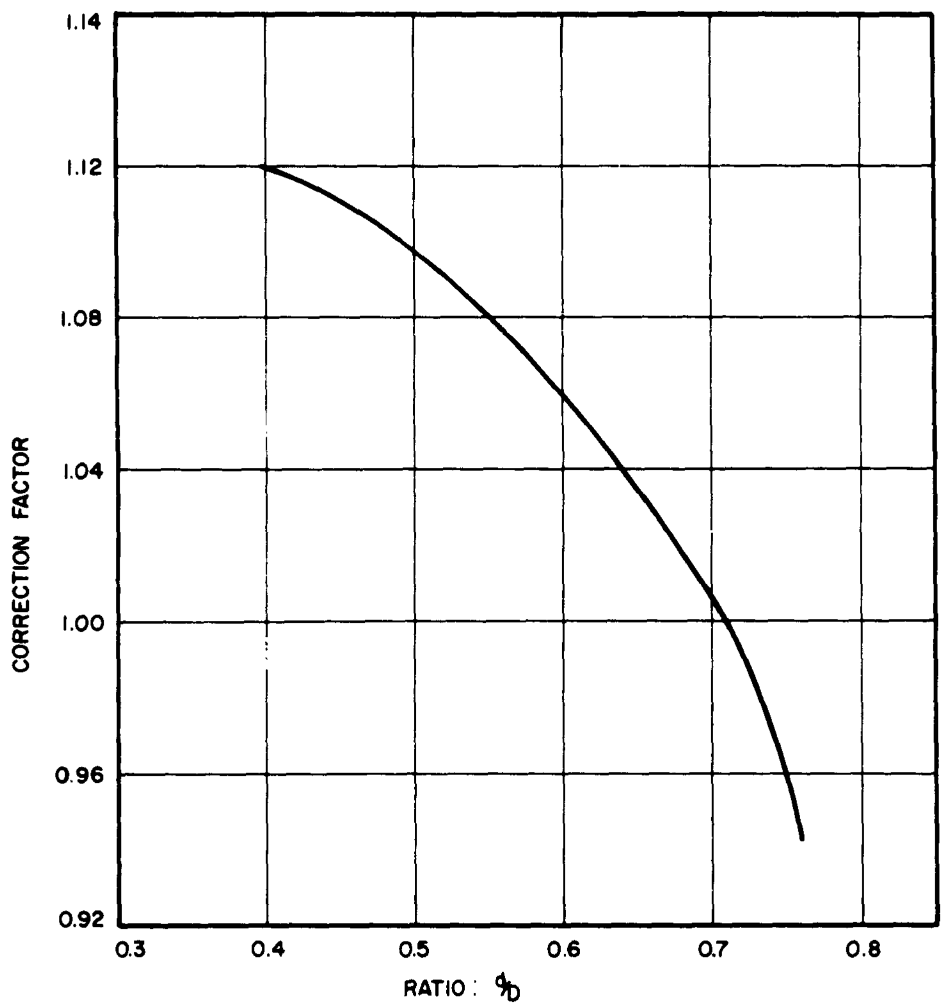

FIG.18: CORRECTION FACTOR EMPLOYED FOR DETERMINING K_{IC} FROM SPECIMENS WITH VARYING d/D RATIOS.

TABLE III

Tensile Properties of Beta Titanium (B120 VCA) Sheet
(185,000 psi Strength Level-Heat F7769)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation (in/in)	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-100 (long.)	198,200	194,900	2.0	40,300	23,500
	209,300	207,900	2.0	40,600	27,400
				40,600	25,800
Average	203,750	200,400	2.0	40,500	25,600
0 (long.)	189,300	180,100	3.0	40,000	23,400
	192,900	185,500	2.5	46,100	26,200
				47,800	27,200
Average	191,100	182,800	2.8	44,600	25,600
75 (long.)	185,800	174,300	3.5	56,200	33,900
	188,700	174,500	4.0	45,400	25,700
				52,800	30,600
	187,250	174,400	3.8	51,500	30,000
75 (trans.)	188,300	181,100	3.0	42,600	27,600
	193,400	183,600	2.0	43,000	24,100
Average	190,850	182,350	2.5	42,800	25,850
200 (long.)	183,300	161,800	5.0	68,000	32,300
	176,400	158,600	4.0	66,400	31,800
				63,800	36,000
Average	179,850	160,200	4.5	66,050	33,350
300 (long.)	182,500	159,100	5.0	69,700	34,800
	171,200	155,100	3.5	78,800	39,700
	177,600	154,100		83,100	41,700
				79,800	
Average	177,100	156,100	4.2	77,850	38,700

TABLE IV

Tensile Properties of Beta Titanium (B120VCA) Sheet

(170,000 psi Strength Level-Heat F 7798)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation (in/in)	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-100 (long)	172,800		1.5	38,600	22,700
	186,800	182,400	1.0	42,100	23,200
				39,800	24,200
Average	179,800	182,400	1.2	40,150	23,350
0 (long.)	172,700	169,500	2.0	47,600	28,800
				46,700	24,500
				47,000	32,000
Average	172,700	169,500	2.0	47,100	28,450
75 (long.)	170,500	166,000	1.0	62,800	31,600
	167,500	165,300	1.0	57,400	29,200
				59,600	29,000
Average	169,000	165,600	1.0	59,950	29,950
75 (trans.)	*	*	*	50,900	29,500
				56,500	29,700
				54,200	33,000
Average				53,850	30,750
200 (long.)	168,600	153,600	3.5	71,400	41,700
	166,700	153,600	3.0	81,400	43,100
				71,300	43,400
Average	167,550	153,600	3.2	74,700	42,750
300 (long.)	167,900	145,300	4.0	87,600	44,100
	172,100	146,700	5.0	87,400	41,400
				70,900	35,100
Average	170,000	146,000	4.8	82,000	40,200

* No smooth data obtained due to the pin hole fractures.

TABLE V

Tensile Properties of Beta Titanium (B120 VCA) Bar

(200,000 psi Strength Level-Heat F 6997)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	% El (in/in)	% R.A. (in^2/in^2)	Notch Tensile Strength (psi)	Plane Strain Fracture Toughness ($psi\sqrt{in}$)
-100	217,100	200,700	8.0	8.1	88,900	28,900
	214,700	200,300	5.0	5.1	87,000	26,500
					88,500	27,800
Average	215,900	200,500	6.5	6.6	88,100	27,700
0	200,500	183,400	6.0	4.7	106,000	34,600
	197,000	180,500	7.0	6.6	101,200	32,300
					101,500	32,900
Average	198,750	181,950	6.5	5.6	102,900	33,300
75	198,700	179,400	11.0	9.7	94,400	30,600
	198,100	183,400	3.5	3.1	96,200	32,300
					106,700	32,600
Average	198,400	181,400	7.2	6.4	99,100	31,900
200	192,900	165,200	9.0	7.8	111,000	35,700
	189,000	161,500	12.5	14.4	119,000	36,300
					121,500	41,700
Average	190,950	163,350	10.8	11.3	117,000	37,900
300	191,700	159,400	11.0	13.8	123,500	40,700
	191,700	159,000	10.0	13.8	120,500	38,600
					121,900	38,100
Average	191,700	159,200	10.5	13.8	122,000	39,100

TABLE VI

Tensile Properties of 4340 Steel

(280,000 psi Strength Level-Heat 7C-8236)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation (in/in)	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-100 (long.)	284,000	225,000	12.0	85,600	37,900
	283,000	225,000	11.0	77,100	39,300
				84,500	39,200
Average	283,500	225,000	11.5	82,400	38,800
0 (long.)	279,000	223,000	10.0	95,200	38,200
	280,000	222,000	10.0	98,500	39,100
				102,300	39,900
Average	279,500	222,500	10.0	98,650	39,050
75 (long.)	279,200	219,000	11.0	114,000	46,900
	280,800	217,000	11.0	104,800	45,100
				103,000	42,400
Average	280,000	218,000	11.0	107,250	44,800
75 (trans.)	284,200	225,000	9.0	96,600	39,300
	285,900	223,000	9.0	98,700	38,500
				98,700	42,000
Average	285,050	224,000	9.0	98,000	39,950
200 (long.)	287,000	223,000	10.0	96,600	37,000
	287,000	220,000	10.0	98,300	37,700
				101,000	40,300
Average	287,000	221,500	10.0	98,650	38,350
300 (long.)	290,000	186,000	13.0	83,200	38,800
	286,000	192,500	13.0	77,700	39,400
				79,900	38,500
Average	288,000	189,250	13.0	80,250	38,900

TABLE VII

Tensile Properties of 4340 Steel Sheet
(280,000 psi Strength Level-Heat 7C-8657)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation (in/in)	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-100 (long.)	289,000	224,000	11.0	71,900	40,300
	289,000	225,000	13.0	61,100	33,000
				70,200	34,800
Average	289,000	224,500	12.0	67,750	36,050
0 (long.)	283,000	220,000	10.0	94,100	40,000
	283,000	221,000	11.0	80,000	37,900
				78,800	35,500
Average	283,000	220,500	10.5	84,300	37,800
75 (long.)	284,000	222,000	10.0	82,000	32,300
	281,000	225,100	7.0	83,000	36,100
				78,100	37,300
Average	282,500	223,550	8.5	81,050	35,250
25 (trans.)	290,100	223,000	10.0	86,800	35,700
	292,900	224,000	9.5	94,000	36,400
				87,200	35,400
Average	291,500	223,500	9.8	89,350	35,850
200 (long.)	288,000	227,000	9.0	76,450	31,700
	287,600	216,000	10.0	77,200	34,800
				79,900	35,500
Average	287,800	221,500	9.5	77,850	34,000
300 (long.)	288,000	197,000	9.0	67,900	34,000
	290,000	188,000	10.0	71,600	34,400
				66,300	30,800
Average	289,000	192,500	9.5	68,600	33,050

TABLE VIII

Tensile Properties of 4340 Steel Bar
(280,000 psi Strength Level-Heat 124515)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	% El (in/in)	% R.A. (in^2/in^2)	Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi√in)
-100	283,500	227,000	15.0	50.1	129,000	41,900
	288,300	221,800	15.0	51.8	121,500	39,800
					139,500	45,600
Average	285,900	224,400	15.0	51.0	130,000	42,400
0	283,300	217,900	15.0	48.4	161,500	52,000
	282,300	221,400	16.0	48.6	147,500	47,900
					180,100	56,500
Average	282,800	219,650	15.5	48.5	163,000	52,100
75	281,900	220,900	15.0	50.7	163,000	51,600
	280,700	221,000	16.0	49.0	183,000	59,600
					176,000	55,400
Average	281,300	220,950	15.5	49.8	174,000	55,500
200	285,500	216,900	14.0	41.3	135,000	47,200
	282,300	216,500	13.5	42.0	148,000	49,200
					154,500	48,400
Average	283,900	216,700	13.8	41.6	145,000	48,300
300	288,100	192,000	18.0	45.5	127,000	39,900
	289,900	198,000	19.0	41.3	137,000	43,600
					132,000	42,000
Average	289,000	195,000	18.5	43.4	132,000	41,800

TABLE IX

Tensile Properties of 4340 Steel Sheet

(200,000 psi Strength Level-Heat 7C-8657)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation (in/in)	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi√in)
-100 (long.)	219,000	207,000	8.0	159,000	58,400
	219,000	203,000	10.0	167,000	66,600
				158,000	57,900
Average	219,000	205,000	9.0	161,350	60,950
0 (long.)	213,000	199,000	10.0	157,000	51,300
	209,000	196,000	9.0	155,000	57,200
				163,000	60,000
Average	211,000	197,500	9.3	158,350	56,150
75 (long.)	214,300	200,500	7.5	151,800	63,900
	212,200	196,600	8.0	156,400	59,000
				151,800	64,500
Average	213,250	198,550	7.8	153,350	62,450
75 (trans.)	210,100	194,600	7.5	127,000	55,500
	212,200	196,100	8.0	139,600	52,600
				128,800	45,800
Average	211,150	195,350	7.8	131,800	51,300
200 (long.)	207,500	184,700	9.0	171,000	67,200
	207,500	182,500	8.5	149,200	63,500
				146,600	61,000
Average	207,500	183,600	8.8	155,600	63,900
300 (long.)	209,300	180,300	9.0	134,800	50,800
	207,100	175,600	9.0	142,800	41,600
				146,200	54,100
Average	208,200	177,950	9.0	141,250	48,850

TABLE X

Tensile Properties of 4340 Steel Sheet

(200,000 psi Strength Level-Heat 7C-8236)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation (in/in)	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-100 (long.)	219,000	209,000	9.0	172,000	75,600
	219,500	205,000	10.0	170,000	72,100
					81,000
Average	219,250	207,000	9.5	171,000	76,200
0 (long.)	213,000	197,500	9.0	160,500	86,900
	212,000	197,500	8.0	173,000	79,500
				170,300	71,200
Average	212,500	197,500	8.5	168,000	79,200
75 (long.)	213,700	199,200	9.0	180,100	71,900
	210,400	196,500	10.0	166,500	64,900
				163,200	75,400
Average	212,050	197,850	9.5	169,950	70,750
75 (trans.)	213,400	199,600	9.0	142,000	51,500
	211,500	196,600	8.0	140,800	50,400
				126,000	53,100
Average	212,450	198,100	8.5	136,250	51,650
200 (long.)	206,200	184,800	8.0	145,000	59,200
	208,000	185,300	7.5	148,400	70,000
				151,600	69,400
Average	207,100	185,050	7.8	148,350	66,200
300 (long.)	209,200	174,100	9.0	145,200	*
	206,600	178,200	8.5	151,100	
				146,900	
Average	207,900	176,150	8.8	147,750	

* Tests not completed at time report was compiled.

TABLE XI

Tensile Properties of 4340 Steel Bar

(200,000 psi Strength Level-Heat 124515)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	% El (in/in)	% R.A. (in^2/in^2)	Notch Tensile Strength (psi)	Plance Strain Fracture Toughness (psi$\sqrt{in}$)
-100	221,300	205,700	14.0	50.7	255,000	90,100
	220,500	206,800	14.0	50.7	260,000	86,600
Average	220,900	206,250	14.0	50.7	257,000	88,300
0	212,500	200,000	14.5	51.8	248,000	85,500
	212,300	198,300	14.5	51.8	274,000	97,500
					263,000	90,600
Average	212,400	199,150	14.5	51.8	262,000	91,200
75	212,500	197,500	14.0	53.9	264,000	93,400
	213,500	198,200	13.0	48.4	273,000	97,400
					252,000	85,000
Average	213,000	197,850	13.5	51.2	263,000	91,900
200	210,300	185,400	14.5	51.8	226,000	75,100
	207,300	184,600	14.0	50.7	233,000	80,500
					223,000	75,100
Average	208,800	185,000	14.2	51.2	227,000	76,900
300	207,000	173,000	16.0	53.4	197,000	66,400
	209,500	178,400	15.0	46.1	226,000	74,600
					232,000	87,000
Average	208,600	175,700	15.5	49.8	218,000	76,000

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